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On simultaneous tilt and creep observations on the San Andreas Fault

THE installation of an array of tiltmeters along the San Andreas Fault[1] has provided an excellent opportunity to study the amplitude and spatial scale of the tilt fields associated with fault creep. We report here preliminary results from, and some implications of, a search for interrelated surface tilts and creep event observations at four pairs of tiltmeters and creepmeters along an active 20-km stretch of the San Andreas Fault. We have observed clear creep-related tilts above the instrument resolution (10^{-8} rad) only on a tiltmeter less than 0.5 km from the fault. The tilt events always preceded surface creep observations by 2–12 min, and were not purely transient in character.

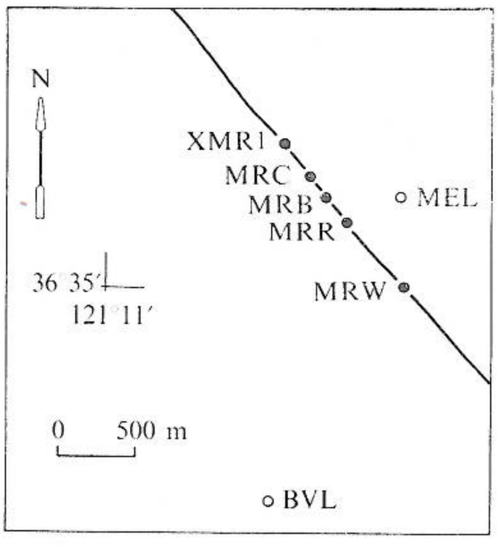

Fig. 1 Location map in the Bear Valley region of central California of tiltmeters (MEL and BVL) and creepmeters (MRW, MRR, MRB, MRC and XMR1) along the San Andreas Fault.

Although episodic fault creep has been observed at many locations of the San Andreas, Hayward, Calaveras, and other active faults in the San Andreas Fault System[2–8], measurements of transient tilts and strains associated with creep events have not yet been made in sufficient detail to allow estimates of critical parameters such as depth, dimension, amount of slip, and the effects of material property variations. These parameters are critical to questions concerning, first, the degree to which the dynamic aseismic slip behaviour of the fault is reflected in fault creep measurements; second the relationship between observed creep and seismicity; and third, the source of the nonlinear form of the creep signals. Typical creep events have amplitudes of a few millimetres and durations of a few minutes to a few days[8,9]. Fault displacements inferred from cumulative creep[10] are in approximate agreement with those measured using geodetic techniques[11], and approximately simultaneous observations of creep events at closely spaced creepmeter sites have been interpreted as slip propagation along the fault at rates of up to 10 km d^{-1} (refs 4 and 6).

With one exception, the tiltmeters considered here form part of an array of shallow borehole instruments approximately 6 km apart, and 1–2 km from the fault (Fig. 1), intended primarily for the detection of earthquake related deformation[1]. The exception is the tiltmeter at Melendy Ranch (MEL) which was installed 370 m from the fault near several Melendy Ranch creepmeters. This instrument grouping, in addition to tiltmeter MEL on the north-east side of the fault, consists of creepmeters XMR1, MRC, MRB, MRR, and MRW along the fault from north-west to south-east, and tiltmeter BVL on the south-west side of the fault, as shown in Fig. 1. At these creepmeters clear examples of episodic creep on the San Andreas Fault are observed every few months[8,9].

Since January, 1974, three of the largest creep events, each recorded on at least two creepmeters, have occurred while both tiltmeters were operating. Figure 2 shows about 6 h of parallel record from the two tiltmeters and the particular creepmeters in operation at the time of these creep events. The uncertainty in timing for all sets of records is less than 2 min.

For the first creep sequence of July 11, 1974 (Fig. 2*a*) creep was recorded only on meters MRC and XMR1 to the north-west of MEL. The times of onset were 1745 and 1808 GMT, respectively. For more than an hour before 1743 a ramp-like change is evident in the north–south tilt component at MEL (Fig. 2*a*). Although interesting, this is

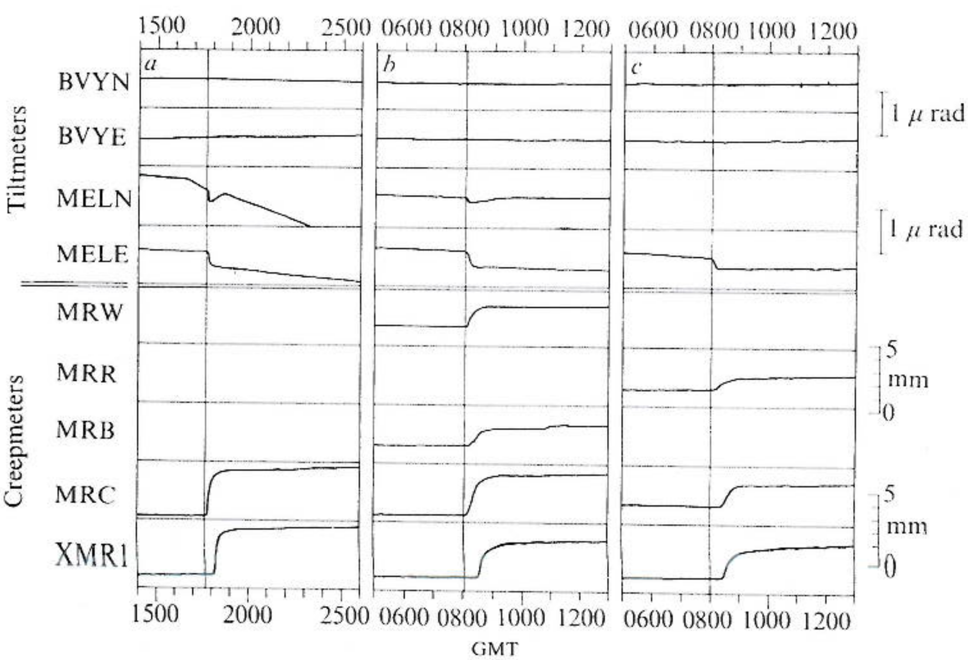

Fig. 2 Three examples of approximately 6 h of simultaneous digitised records from creepmeters XMR1, MRC, MRB, MRR and MRW and tiltmeters BVL and MEL during creep events on: *a*, July 11, 1974; *b*, October 3, 1974; *c*, April 14, 1975. BVLN, MELN, and BVLE, MELE are the north and east components, respectively. Absence of data indicates an instrument malfunction.

the only example of a tilt ramp of this sort, and its meaning is not clear. From 1743 to 1800 the tilt at MEL increased by 0.5 μrad in a direction S41°W. The amplitude decreased and the direction changed slowly clockwise during the next 30 min, finally resulting in a tilt of 0.4 μrad towards the west. No significant changes occurred in the tilt record at BVL (resolution 10^{-2} μrad) during this time.

A second creep sequence, on October 3, 1974 (Fig. 2*b*), is more important since it was observed on the four creepmeters MRW, MRB, MRC, and XMR1 along the fault from the south and to the north-west of MEL. The first onset of creep occurred at 0812 at MRC. Almost simultaneous offsets occurred next at MRW and MRB at 0815 followed by XMR1 at 0837. The tilt changed at MEL between 0800 and 0815 by 0.52 μrad in a direction S72°W, and during the next hour this amplitude decreased and the direction changed slightly clockwise until reaching a final tilt offset value of 0.36 μrad in a westerly direction. The tilt records at BVL were again unchanged.

The creep sequence on April 14, 1975 (Fig. 2*c*) was recorded on MRR at 0805, followed by MRC at 0821 and on XMR1 at 0826. Only the east–west tilt component was operating at MEL during this time. This record shows a tilt change of 0.25 μrad between 0800 and 0807 similar to that observed for the earlier creep sequences.

For the next pair of instruments to the north, creepmeter XFL1 and tiltmeter SAS with a 2-km separation, five creep sequences have occurred since June, 1973 when simultaneous recording began. Tiltmeter SAS is 1.2 km from the fault. At that distance, as for BVL, no clear relationship between the creep events and either short or intermediate term tilts has been found. This is true also for the northernmost instrument pair considered; creepmeter XPR1 and the tiltmeter LIB, separated by 3.4 km with LIB 1.5 km from the fault.

Creep-related tilts seem, therefore, to be rapidly attenuated as a function of distance from the fault. At Melendy Ranch, in particular, a displacement of a few millimetres on the fault that results in a tilt of 0.5 μrad at 370 m and less than 0.01 μrad at 1,500 m implies at least inverse cube attenuation with distance. This may be expected from either a small scale or shallow source or a slightly decreased rigidity in or near the fault zone. The latter possibility seems most likely since the surface displacements extend at least 1.2 km along the fault trace for the Melendy observations and seem in other cases to extend to several tens of kilometres[6]. This would also explain why a search for interrelationship between short period tilt changes on adjacent tiltmeters has so far been inconclusive.

The tilt signals for all three events are similar and therefore indicate a similar source process. The residual west tilt observed at MEL for the creep events, and the general systematic later arrivals and lower amplitudes of these and other creep events between MRC and XMR[8,9], indicate that the slip amplitude and/or the propagation velocity probably vary as the events propagate. Even with decreasing propagation velocity and slip amplitude to the north, however, the form of the tilt and the nearly simultaneous onset times for tilt and creep during the October 3 event (Fig. 2*b*) are difficult to fit with a single simple model of horizontal slip propagating northwards. The introduction of a vertical slip component (south-western side up) over a limited extent of the fault with a local maximum between MRB and MRC, together with horizontal slip, can generate time histories similar to those observed. The accumulated vertical displacement necessary as a consequence of this model is indicated by the presence of a north-easterly-facing scarp along the fault trace from MRW to MRC, with increasing scarp height to the north-west (the point of maximum development is about 3.5 m between MRB and MCR).

Most records of other creep events at Melendy Ranch display regular patterns of onset times[8,9] although variations similar to those for the October 3 and April 14 events occur. Simple slip models, such as indicated above, are not always compatible with the detailed onset times and the creep amplitudes. It is possible that the exact onset times of creep, and perhaps also the amplitudes, result from, or are modified by, the particular local failure conditions of the surface material. More examples on a supplemented tilt and strain array in this area should clarify many of these details and make a rigorous inversion possible.

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